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Mass of decaying wino from AMS-02 2014

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ABSTRACT

We revisit the decaying wino dark matter scenario in the light of the updated positron fraction, electron and positron fluxes in cosmic ray recently reported by the AMS-02 collaboration. We show the AMS-02 results favor the mass of the wino dark matter at around a few TeV, which is consistent with the prediction on the wino mass in the pure gravity mediation model.

1. Introduction

The AMS-02 collaboration has recently updated the positron fraction, the electron flux, and the positron flux in cosmic ray [1,2], which consistently show anomalous excesses over the expectation based on the conventional cosmic-ray propagation model. Of particular interest of these new results is that the positron fraction is no longer increasing with energy above around 200 GeV. Furthermore, the positron fraction and flux look to peak at around 300 GeV. If the anomalous excesses come from the decaying dark matter, such "peak" structures give constraints on the dark matter mass. In this letter, we revisit the decaying wino dark matter scenario [3] to account for the anomalous excesses, and derive the constraint on the decaying wino mass along the line of the analysis of our previous paper [4].

From phenomenological viewpoint, the wino-like dark matter is a good candidate for weakly interacting massive particle (WIMP) that evades severe limits from direct detection searches [5]. On the other hand, the dark matter predicts strong signals in indirect detection searches utilizing e.g. gamma-ray observations, for its annihilation cross section is boosted by the Sommerfeld enhancement [6,7]. Though the strength of the signal is still below current experimental limits due to large astrophysical ambiguities, they are expected to be detected in near future [8].

From theoretical viewpoint, the wino-like dark matter is realized in a wide class of supersymmetric standard models when gaugino masses are dominated by the anomaly mediated supersymmetry breaking contributions [9]. Models with anomaly mediated gaugino mass are now highly motivated since they provide a good dark matter candidate (i.e. the wino) while explaining the observed Higgs boson mass of about 126 GeV [10] in conjunction with the high scale supersymmetry breaking where the gravitino and the sfermion masses are in $\mathcal{O}(100\text{–}1000)$ TeV range [11]. Such models are, for example, realized as the models of pure gravity mediation (PGM) [12–14], the models with strong moduli stabilization [15], the spread supersymmetry [16], and the minimal split supersymmetry [17]. As we will show, the recent observations of AMS-02 suggest the decaying wino mass is at around a few TeV, which is consistent with the prediction on the wino mass in this class of models.

2. Decaying wino in the PGM model

Let us briefly summarize the decaying wino dark matter scenario in the pure gravity mediation model. In the model, gaugino masses are dominated by the one-loop anomaly mediated contributions [9], and the neutral wino becomes the lightest supersymmetric (LSP). For derivation of the anomaly mediated gaugino masses in superspace formalism of supergravity, refer to the papers [18–20]. The Higgsino mass term is, on the other hand, generated through tree-level interactions to the R-symmetry breaking sector [21] (the generalized Giudice–Masiero mechanism [22]), which leads to the Higgsinos mass much larger than the gaugino masses. With such a large Higgsino mass term, the mixing between the wino and the bino is highly suppressed. The PGM model therefore predicts the almost pure neutral wino as the LSP which is a good candidate for WIMP dark matter.

The wino dark matter is produced thermally in the early universe and non-thermally by the decay of the gravitino in the late

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universe before the big bang nucleosynthesis (BBN) starts. Putting these contributions together, the wino mass turns out to be lighter than about 3 TeV in order to be consistent with the observed dark matter density [23]. The wino mass of around 3 TeV is particularly interesting, because the dark matter density is explained solely by its thermal relic density [24]. The wino dark matter lighter than 3 TeV can also provide the correct relic density when the non-thermal production dominates, [25,26,12]. In particular, the wino mass below about 1–1.5 TeV is interesting, because such a lighter wino dark matter is easily consistent with the traditional thermal leptogenesis scenario [27].

The wino dark matter is not necessarily to be absolutely stable and may decay into standard model particles when the R-parity is slightly violated. In this letter, we consider the decay caused by R-parity violating interactions,

$$\mathcal{W}_{\not R} = \lambda_{ijk} L_i L_j E^c_k, \tag{1}$$

among various possibilities to violate the R-parity. Here, the indices denote the generation of leptons, and λ's are tiny coupling constants. The decaying wino dark matter via the LLE^c interactions is free from the constraint from cosmic-ray anti-proton observations.[1] Constraints from gamma-ray observations are also much milder than the case of models with R-parity violation by LH_u [3]. Through the R-parity violating interactions in Eq. (1), the wino dark matter decays into three-body final states that are composed only of leptons (a pair of charged leptons and a neutrino). Its lifetime is estimated to be as follows [28]:

$$\tau_{\rm wino} \sim 10^{27} \left(\lambda/10^{-19}\right)^{-2} (m_{\rm wino}/1~{\rm TeV})^{-5} \left(m_{\tilde{L}}/10^3~{\rm TeV}\right)^4~{\rm s}. \tag{2}$$

Electron and positron cosmic rays from the decay reproduce the anomalous excesses of AMS-02 for $\tau_{\rm wino} = O(10^{26-27})$ s, as will be seen in the next subsection.

3. Wino mass from AMS-02 2014

The procedure to calculate the electron and positron fluxes for signal and background is essentially the same as the one adopted in our previous paper [4]. We made several assumptions in the procedure, and those are listed below in order.

- The decay of the wino dark matter is described by the interaction $L_i L_j E^c_k$. Primary e^+ and e^- spectra from the decay are obtained assuming the left-handed slepton $\tilde{L}_i$ is enough lighter than others and no flavor violation exists on couplings between wino and (s)leptons. We have used Pythia 8 [29] for the spectra with a slight modification for a polarized lepton decay. The dark matter mass density of our galaxy is assumed to follow the NFW profile [30] with profile parameters $\rho_\odot = 0.4~{\rm GeV/cm^3}$ (the local halo density), $r_c = 20$ kpc (the core radius), and $r_\odot = 8.5$ kpc (the distance between our solar system and the galactic center). Propagations of the electrons and positrons in our galaxy are considered using the diffusion equation of the so-called MED model [31].
- For astrophysical backgrounds against the signals, we have adopted a similar method developed in reference [32]. Using parameters $A^\pm$ and $p^\pm$, background fluxes are parameterized as $\Phi^{e^\pm}_{\rm BG}(E) = A^\pm E^{p^\pm} \Phi^{e^\pm}_{\rm ref}(E)$. Here, $\Phi^{e^\pm}_{\rm ref}(E)$ are reference background fluxes obtained by GALPROP [33] with the electron injection index being -2.66. The effect of the solar modulation is also considered by the force-field method [34] in both signal and background calculations.
- The above electron and positron fluxes are fitted to the latest AMS-02 data of the positron fraction [1] and the electron flux [2]. Following six parameters, the background parameters ($A^\pm$, $p^\pm$) and the force-field potentials for electrons and positrons ($\phi^\pm$), are varied to maximize the likelihood function of the fitting for each wino mass and lifetime ($m_{\rm wino}$ and $\tau_{\rm wino}$) in the ranges of $A^\pm \in [0, \infty]$, $p^\pm \in [-0.5, 0.5]$, and $\phi^\pm \in [0, 1]$ GV, respectively. The fitting has been performed in the energy range of $E > 5$ GeV for the positron fraction and > 10 GeV for the electron flux to suppress the effect of the solar modulation.

Fitting results are depicted in upper three panels of Fig. 1 as contour lines of 68th, 95th, and 99th percentile of the chi-squared distribution for two degrees of freedom. The results for the wino decays caused by the interactions $L_1 L_2 E^c_i$, $L_3 L_1 E^c_i$, and $L_3 L_2 E^c_i$ ($i = 1, 2$, and 3) are shown in top-left, top-right, and middle-left panels, respectively. As a reference, the wino mass favored by the thermal WIMP scenario is shown as a light yellow bar. In lower three panels of the figure, as an example, the positron fraction (middle-right panel), the electron flux (bottom-left panel), and the positron flux (bottom-right panel) are shown with the latest AMS-02 data for the decay caused by the interaction $L_3 L_2 E^c_1$. The red solid lines in these plots are from the best-fit parameters of $m_{\rm wino}$ and $\tau_{\rm wino}$, while red shaded regions are obtained by the parameters within 68th percentile of the chi-squared distribution.

Constraints on the wino mass from other experiments are also shown in the upper three panels as regions shaded by grays: The dark gray region in each panel is from the disappearing charged track search at the Large Hadron Collider experiment [35,36]. The light gray region is from the Fermi-LAT experiment [37], which is obtained by observing gamma-rays from the wino dark matter annihilation at classical dwarf spheroidal galaxies. This observation is known to give the most robust limit on the wino mass among various indirect detection searches of dark matter [8].

The decay of the wino also generates energetic gamma-rays through prompt decay as well as the inverse Compton scattering (ICS). Such high energetic gamma-rays are again constrained by the Fermi-LAT observations. By repeating the analysis in [4], we find that the observation gives the constraint as $\tau_{\rm wino} \gtrsim 10^{26}$ s in the region of $m_{\rm wino} \sim 1$ TeV when we use officially published data of the Fermi-LAT experiment [38,39]. As a result, the gamma-ray constraints by the Fermi-LAT experiments have some tension with the models with operators including L_3 and/or E^c_3, since they require rather shorter lifetimes to account for the positron excess. We did not explicitly show the constraint on the panels to avoid making the figure busy.

As a word of caution, the contribution from the ICS in the galactic halo has not been included in the above mentioned analysis in [4], since it is subject to the uncertainties on the global distribution of the diffused electrons and positrons in the galactic halo.[2] We have included the ICS with the cosmic microwave background caused by the wino decay at all past redshifts. With our conservative estimation, the constraints in our analysis are weaker than the ones in [40].[3]

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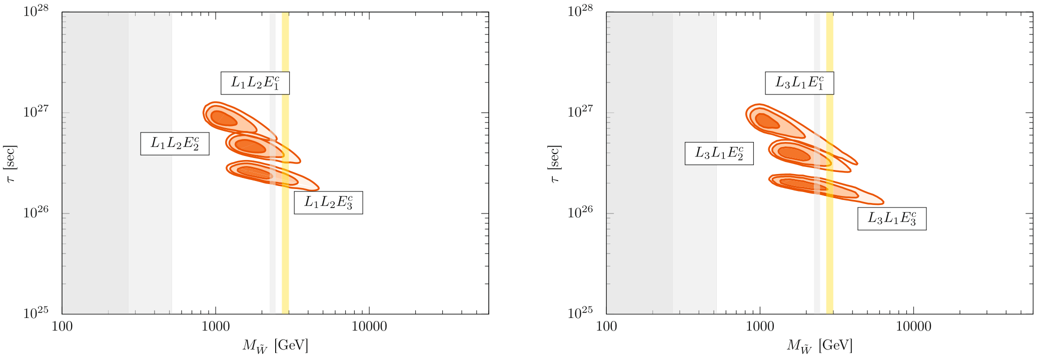
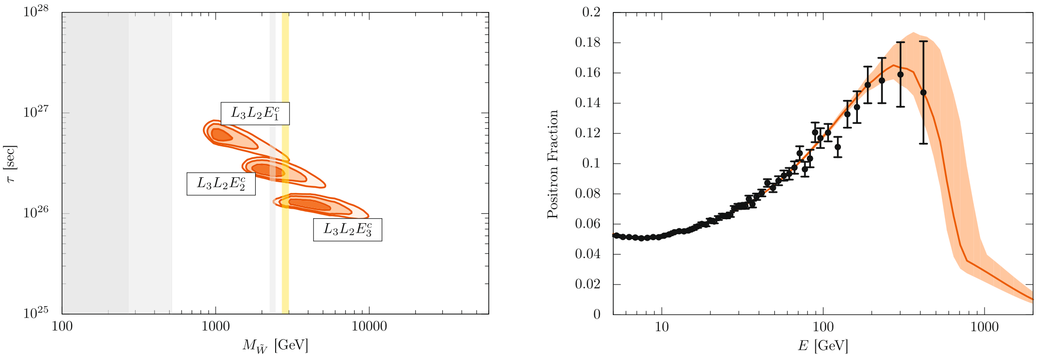
[1] We presume the absence of other R-parity violating operators. As discussed in reference [4], it is possible to generate only LLE^c operators in a grand unified theory consistent way.

[2] The electron/positrons fluxes observed by PAMELA/Fermi-LAT/AMS-02 are local ones, and hence, the signal rate from the wino decay is not subject to these uncertainties.

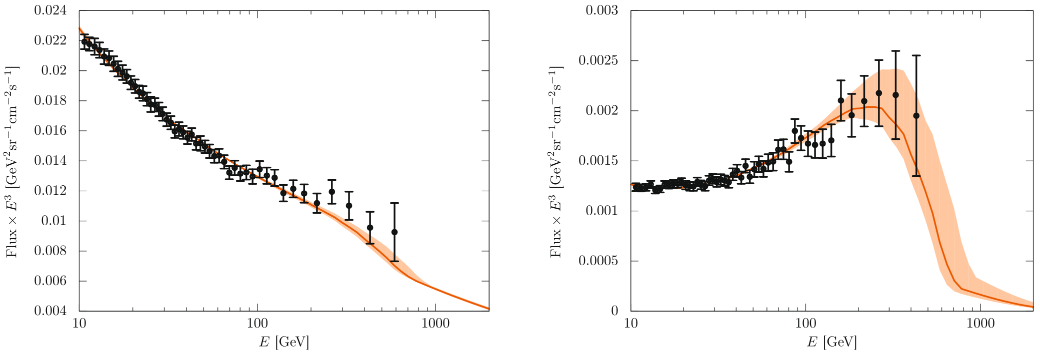
[3] In [40], it is also discussed how the constraints from the gamma ray flux are relaxed for conservative estimation and found that the decaying DM scenario in



(a) $L_1L_2E_k^c$ (b) $L_3L_1E_k^c$



(c) $L_3L_2E_k^c$ (d) $L_3L_1E_2^c$ positron fraction



(e) $L_3L_1E_2^c$ electron flux (f) $L_3L_1E_2^c$ positron flux

Fig. 1. *Upper three panels*: Contour lines of 68th, 95th, and 99th percentile of the likelihood function (the chi-squared distribution) for the wino decays through the interactions $L_1L_2E_i^c$ (top-left panel), $L_3L_1E_i^c$ (top-right panel), and $L_3L_2E_i^c$ (middle-left panel), where $i = 1, 2$, and 3. See text for gray and yellow shaded regions. *Lower three panels*: The positron fraction (middle-right panel), the electron flux (bottom-left panel), and the positron flux (bottom-right panel) with the latest AMS-02 data for the decay through the interaction $L_3L_1E_2^c$. See text for red solid lines and red shaded regions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As can be seen from the figure, the decaying wino dark matter with LLE^c interactions is indeed very consistent with the latest AMS-02 data. In particular, the wino mass favored by the data is always within a few TeV region irrespective to the lepton flavor structure of the interaction $L_iL_jE_k^c$, which is nothing but the region predicted by the pure gravity mediation model. As mentioned above, the limit from the diffuse gamma-ray observation seems to start excluding the favored parameter region when the wino decays mainly into tau leptons, such as the decays caused by the $L_3L_1E_3^c$ and $L_3L_3E_3^c$ interactions. On the other hand, the decays mainly into first and second generation leptons are still away from the limit. For the sake of convenience, we have also estimated the uncertainty associated with electron and positron propagations in our galaxy using the diffusion equations of the so-called M1 and M2 models. The uncertainty turns out not to change the result drastically.

4. Summary and discussions

We have revisited the decaying wino dark matter scenario in the light of the updated positron fraction, electron flux, and positron flux in cosmic ray reported by the AMS-02 collaboration. The AMS-02 data can be well explained by the almost pure wino dark matter of its mass around a few TeV and its decay described by the R-parity violating LLE^c interactions. Such a dark matter, in particular a few TeV range of the wino mass, is consistent with the pure gravity mediation model very well.

PAMELA+Fermi region still survives. Therefore, our analysis is more conservative but consistent with [40].

The origin of the anomalous excess reported by the AMS-02 collaboration is still unknown: Both dark matter interpretation and astrophysical interpretation such as pulsar activities nearby us may be still possible (for recent discussions see [41–43] and references therein). Future observations of extragalactic diffuse gamma-rays caused by the wino decay and those of gamma-rays caused by the wino dark matter annihilation at dwarf spheroidal galaxies will be important to convince us that the wino dark matter is really the origin.

If the R-parity breaking operators such as $U^c U^c D^c$ or $Q D^c L$ are not completely suppressed, the wino decay may have the hadronic modes. If it is the case, we may have antiproton excess in the cosmic ray.

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References

[1] L. Accardo, AMS Collaboration, Phys. Rev. Lett. 113 (2014) 121101.

[2] M. Aguilar, AMS Collaboration, Phys. Rev. Lett. 113 (2014) 121102.

[3] S. Shirai, F. Takahashi, T.T. Yanagida, Phys. Lett. B 680 (2009) 485, arXiv:0905.0388 [hep-ph].

[4] M. Ibe, S. Matsumoto, S. Shirai, T.T. Yanagida, J. High Energy Phys. 1307 (2013) 063, arXiv:1305.0084 [hep-ph].

[5] J. Hisano, K. Ishiwata, N. Nagata, Phys. Rev. D 87 (2013) 035020, arXiv:1210.5985 [hep-ph].

[6] J. Hisano, S. Matsumoto, M.M. Nojiri, Phys. Rev. Lett. 92 (2004) 031303, arXiv:hep-ph/0307216.

[7] J. Hisano, S. Matsumoto, M.M. Nojiri, O. Saito, Phys. Rev. D 71 (2005) 063528, arXiv:hep-ph/0412403.

[8] B. Bhattacherjee, M. Ibe, K. Ichikawa, S. Matsumoto, K. Nishiyama, J. High Energy Phys. 1407 (2014) 080, arXiv:1405.4914 [hep-ph].

[9] G.F. Giudice, M.A. Luty, H. Murayama, R. Rattazzi, J. High Energy Phys. 9812 (1998) 027, arXiv:hep-ph/9810442;
L. Randall, R. Sundrum, Nucl. Phys. B 557 (1999) 79, arXiv:hep-th/9810155;
M. Dine, D. MacIntire, Phys. Rev. D 46 (1992) 2594, arXiv:hep-ph/9205227.

[10] Y. Okada, M. Yamaguchi, T. Yanagida, Prog. Theor. Phys. 85 (1991) 1;
Y. Okada, M. Yamaguchi, T. Yanagida, Phys. Lett. B 262 (1991) 54;
J.R. Ellis, G. Ridolfi, F. Zwirner, Phys. Lett. B 257 (1991) 83;
H.E. Haber, R. Hempfling, Phys. Rev. Lett. 66 (1991) 1815;
H.E. Haber, R. Hempfling, Phys. Rev. Lett. 66 (1991) 1815;
J.R. Ellis, G. Ridolfi, F. Zwirner, Phys. Lett. B 262 (1991) 477.

[11] J.D. Wells, Phys. Rev. D 71 (2005) 015013, arXiv:hep-ph/0411041.

[12] M. Ibe, T. Moroi, T.T. Yanagida, Phys. Lett. B 644 (2007) 355, arXiv:hep-ph/0610277;
M. Ibe, T.T. Yanagida, Phys. Lett. B 709 (2012) 374, arXiv:1112.2462 [hep-ph];
M. Ibe, S. Matsumoto, T.T. Yanagida, Phys. Rev. D 85 (2012) 095011, arXiv:1202.2253 [hep-ph].

[13] B. Bhattacherjee, B. Feldstein, M. Ibe, S. Matsumoto, T.T. Yanagida, Phys. Rev. D 87 (2013) 015028, arXiv:1207.5453 [hep-ph].

[14] J.L. Evans, M. Ibe, K.A. Olive, T.T. Yanagida, Eur. Phys. J. C 73 (2013) 2468, arXiv:1302.5346 [hep-ph];
J.L. Evans, K.A. Olive, M. Ibe, T.T. Yanagida, Eur. Phys. J. C 73 (2013) 2611, arXiv:1305.7461 [hep-ph];
J.L. Evans, M. Ibe, K.A. Olive, T.T. Yanagida, Eur. Phys. J. C 74 (2014) 2775, arXiv:1312.1984 [hep-ph];
J.L. Evans, M. Ibe, K.A. Olive, T.T. Yanagida, arXiv:1402.5989 [hep-ph];
J.L. Evans, K.A. Olive, arXiv:1408.5102 [hep-ph].

[15] E. Dudas, C. Papineau, S. Pokorski, J. High Energy Phys. 0702 (2007) 028, arXiv:hep-th/0610297;
H. Abe, T. Higaki, T. Kobayashi, Y. Omura, Phys. Rev. D 75 (2007) 025019, arXiv:hep-th/0611024;
R. Kallosh, A. Linde, K.A. Olive, T. Rube, Phys. Rev. D 84 (2011) 083519, arXiv:1106.6025 [hep-th];
A. Linde, Y. Mambrini, K.A. Olive, Phys. Rev. D 85 (2012) 066005, arXiv:1111.1465 [hep-th];
E. Dudas, A. Linde, Y. Mambrini, A. Mustafayev, K.A. Olive, Eur. Phys. J. C 73 (2013) 2268, arXiv:1209.0499 [hep-ph];
J.L. Evans, M.A.G. Garcia, K.A. Olive, J. Cosmol. Astropart. Phys. 1403 (2014) 022, arXiv:1311.0052 [hep-ph].

[16] L.J. Hall, Y. Nomura, J. High Energy Phys. 1201 (2012) 082, arXiv:1111.4519 [hep-ph];
L.J. Hall, Y. Nomura, S. Shirai, J. High Energy Phys. 1301 (2013) 036, arXiv:1210.2395 [hep-ph].

[17] N. Arkani-Hamed, A. Gupta, D.E. Kaplan, N. Weiner, T. Zorawski, arXiv:1212.6971 [hep-ph].

[18] J.A. Bagger, T. Moroi, E. Poppitz, J. High Energy Phys. 0004 (2000) 009, arXiv:hep-th/9911029.

[19] F. D'Eramo, J. Thaler, Z. Thomas, J. High Energy Phys. 1309 (2013) 125, arXiv:1307.3251.

[20] K. Harigaya, M. Ibe, arXiv:1409.5029 [hep-th].

[21] K. Inoue, M. Kawasaki, M. Yamaguchi, T. Yanagida, Phys. Rev. D 45 (1992) 328;
J.A. Casas, C. Munoz, Phys. Lett. B 306 (1993) 288, arXiv:hep-ph/9302227.

[22] G.F. Giudice, A. Masiero, Phys. Lett. B 206 (1988) 480.

[23] P.A.R. Ade, et al., Planck Collaboration, Astron. Astrophys. (2014), arXiv:1303.5076 [astro-ph.CO].

[24] J. Hisano, S. Matsumoto, M. Nagai, O. Saito, M. Senami, Phys. Lett. B 646 (2007) 34, arXiv:hep-ph/0610249.

[25] T. Gherghetta, G.F. Giudice, J.D. Wells, Nucl. Phys. B 559 (1999) 27, arXiv:hep-ph/9904378.

[26] T. Moroi, L. Randall, Nucl. Phys. B 570 (2000) 455, arXiv:hep-ph/9906527.

[27] M. Fukugita, T. Yanagida, Phys. Lett. B 174 (1986) 45;
For reviews, W. Buchmuller, P. Di Bari, M. Plumacher, Ann. Phys. 315 (2005) 305, arXiv:hep-ph/0401240;
W. Buchmuller, R.D. Peccei, T. Yanagida, Annu. Rev. Nucl. Part. Sci. 55 (2005) 311, arXiv:hep-ph/0502169;
S. Davidson, E. Nardi, Y. Nir, Phys. Rep. 466 (2008) 105, arXiv:0802.2962 [hep-ph].

[28] R. Barbier, C. Berat, M. Besancon, M. Chemtob, A. Deandrea, E. Dudas, P. Fayet, S. Lavignac, et al., Phys. Rep. 420 (2005) 1, arXiv:hep-ph/0406039.

[29] T. Sjostrand, S. Mrenna, P.Z. Skands, Comput. Phys. Commun. 178 (2008) 852, arXiv:0710.3820 [hep-ph].

[30] J.F. Navarro, C.S. Frenk, S.D.M. White, Astrophys. J. 490 (1997) 493, arXiv:astro-ph/9611107.

[31] T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527, arXiv:0712.2312 [astro-ph].

[32] M. Cirelli, M. Kadastik, M. Raidal, A. Strumia, Nucl. Phys. B 813 (2009) 1, arXiv:0809.2409 [hep-ph].

[33] A.W. Strong, I.V. Moskalenko, Astrophys. J. 509 (1998) 212, arXiv:astro-ph/9807150.

[34] L.J. Gleeson, W.I. Axford, Astrophys. J. 154 (1968) 1011.

[35] G. Aad, et al., ATLAS Collaboration, Phys. Rev. D 88 (11) (2013) 112006, arXiv:1310.3675 [hep-ex].

[36] M. Ibe, S. Matsumoto, R. Sato, Phys. Lett. B 721 (2013) 252, arXiv:1212.5989 [hep-ph].

[37] M. Ackermann, et al., Fermi-LAT Collaboration, Phys. Rev. D 89 (2014) 042001, arXiv:1310.0828 [astro-ph.HE].

[38] A.A. Abdo, et al., Fermi-LAT Collaboration, Phys. Rev. Lett. 104 (2010) 101101, arXiv:1002.3603 [astro-ph.HE].

[39] M. Ackermann, et al., LAT Collaboration, Phys. Rev. D 86 (2012) 022002, arXiv:1205.2739 [astro-ph.HE].

[40] M. Cirelli, E. Moulin, P. Panci, P.D. Serpico, A. Viana, Phys. Rev. D 86 (2012) 083506, arXiv:1205.5283 [astro-ph.CO].

[41] T. Linden, S. Profumo, Astrophys. J. 772 (2013) 18, arXiv:1304.1791 [astro-ph.HE].

[42] P.F. Yin, Z.H. Yu, Q. Yuan, X.J. Bi, Phys. Rev. D 88 (2) (2013) 023001, arXiv:1304.4128 [astro-ph.HE].

[43] S.J. Lin, Q. Yuan, X.J. Bi, arXiv:1409.6248 [astro-ph.HE].